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A Comparison of Long-Duration Secondary-Power Schemes for Space Vehicles

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The status and limitations of seven basic schemes for converting solar or nuclear radiation to electricity are reviewed. The closed-heat engine cycle employing a hermetically sealed turbo-alternator is selected as the scheme offering the earliest availability for space power applications requiring above a few kilowatts of electrical power. Development problems of the small turbomachinery cycle are emphasized. The conclusion is made that development of the long-duration space power supply may be lagging behind vehicle launch capability.

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The status of power supplies for satellite vehicles today is somewhat reminiscent of the automobile picture in the early 1900's. The vehicle is ready, but the selection of the power

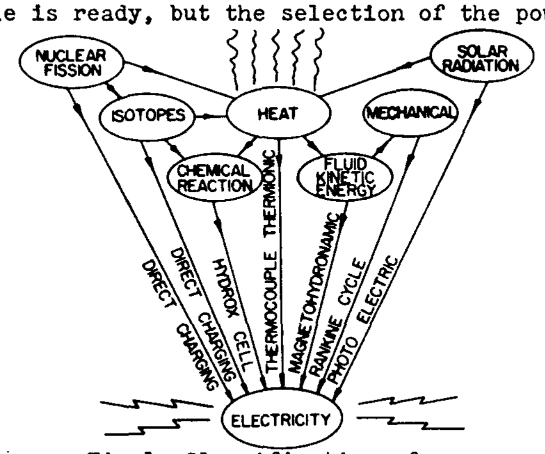


Fig.1 Classification of power conversion.

plant is confused by a bewildering array of possibilities, most in rather infant states of development.

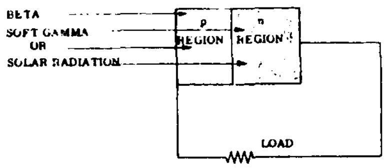
Satellites and space vehicles launched thus far by the U. S. and the U.S.S.R. have had very small power requirements of a few watts, or less. Storage batteries and small solar batteries have been used for these applications, with at least partial success. Missiles with short-duration requirements of several kilowatts are using chemical fueled, turbine-driven alternators successfully. However, the long-duration satellite with a load requirement exceeding several kilowatt-days will require a nuclear or solar auxiliary power unit because of the weight penalty of chemical fuel and oxidant. For example, a 5-kw chemically fueled power supply would require about 5 tons of fuel and oxidant per week in orbit.

POWER CONVERSION SCHEMES

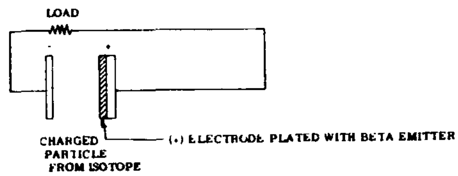
Fig. 1 shows seven classes of possibilities for converting nuclear or solar energy to electricity. Each of these classes has its schemes, and each scheme has proponents. Most of the schemes will require substantial development before they are ready for spaceborne use in a power supply sized above a few kilowatt days of energy.

Direct Conversion

The direct-conversion schemes are attractive because they eliminate moving parts and promise high reliability. However, like heat engines,



DIRECT CONVERSION OF NUCLEAR ENERGY INTO ELECTRICITY BY USE OF A SEMICONDUCTOR



DIRECT CONVERSION OF NUCLEAR ENERGY INTO ELECTRICITY BY THE DIRECT CHARGING METHOD

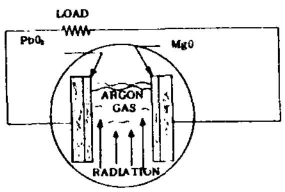


Fig.2 Direct conversion of nuclear energy into electricity by contact potential method.

the direct converters must reject waste heat, and this means that larger direct converters will require heat exchangers, pumps, valves, and controls. For example, using the presently attainable conversion efficiency quoted at a recent M.I.T. symposium on direct conversion, a 5-kw direct converter would require a pumping system and radiator for the dissipation of approximately 70 kw of waste heat. The pump of this waste-heat-removal system alone might require several kilowatts of the highly precious direct conversion electrical power.

Radiation to Electricity

Fig. 2 shows three schemes for directly converting solar or nuclear radiation to electrical

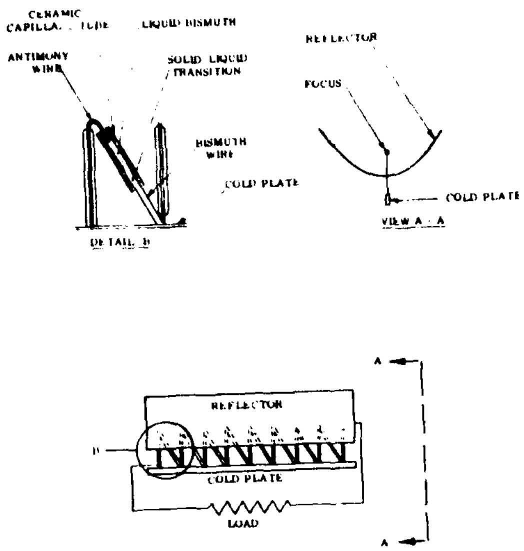


Fig.3 Direct conversion with a thermopile.

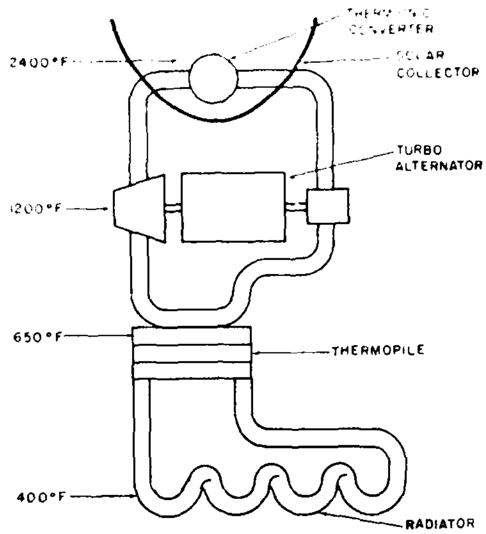


Fig.4 Cascaded conversion schemes.

TABLE 1 PARTIAL LISTING OF ISOTOPES FOR APU POWER SOURCES

	ISOTOPE	HALF LIFE	MELTING POINT - DEGREE C	BOILING POINT - DEGREE C	RADIATION	DOLLARS PER CURIE	DOLLARS COST 5 KW FOR 1 YEAR
1	Strontium - 89	53d	770	1,380	Beta	2,000	1.94 x 10[illegible]
2	Tungsten - 185	73.2d	3,395	5,930	Beta	4,000	2.52 x 10[illegible]
3.	Iridium - 192	74.4d	2,454	5,300	Beta, weak Gamma's	1,000	4.52 x 10[illegible]
4	Sulphur - 35	87.1d	119	445	Beta	4,000	3.72 x 10[illegible]
5	Calcium - 45	163d	850	1,440	Beta	*45,000	7.1 x 10[illegible]
6.	Cerium - 144	282d	780	2,420	Beta, soft Gamma's	1.00	7.37 x 10[illegible]
7.	Ruthenium - 106	*1.0y	2,500	4,900	Beta, Gamma	10,000	5.19 x 10[illegible]
8.	Promethium - 147	2.6y	--	-	Beta	1.75	8.41 x 10[illegible]
9.	Cobalt - 60	5.25y	1,495	2,900	Beta, hard Gamma's	10.00	6.2 x 10[illegible]
10	Strontium - 90	25.0y	770	1,380	Beta	5.00	7.11 x 10[illegible]
11.	Cesium - 137	30.0y	28	690	Beta, Strong Gamma's	1.00	1.465 x 10[illegible]
12.	Nickel - 63	85y	1,455	2,730	Beta	45,000	5.72 x 10[illegible]
13.	Technetium - 99	2.12 x 10[illegible]y	--	--	Beta	80,000	2.31 x 10[illegible]

energy. The most advanced of these schemes, the solar cell, is quite temperature-sensitive under its present state of development, and converts solar to electrical energy at around 4 per cent efficiency. Large batteries of these cells could, conceivably, produce power at a weight power ratio from 200 to 400 lb per kilowatt, depending upon the cell type and the structural support weight.

The increasing availability of radioisotopes make these a potential source of power for space applications.

Radioisotopes are feasible for use in direct-charging converters or in heat-engine cycles. The efficiencies realized thus far in direct conversion schemes appear to be very low. Table 1 illustrates another problem, that of the cost of radioisotopes for larger power supplies. Since the isotope must be supplied in sufficient quantity at launch to make up for the exponential decay with time, the heat-exchanger or power-conversion equipment must be substantially oversized to permit generating rated power at the end of the designed lifetime. Future developments will surely make the use of radioisotopes more attractive, from both a cost and engineering standpoint.

Heat to Electricity

Since solar and nuclear energy are quite readily converted to heat, the direct-heat-to-electrical schemes are worthy of consideration. Fig. 3 shows one scheme for direct-heat-to-electrical conversion.

Conversion efficiencies of the order of 4 to 7 per cent have been reported by experimenters with mixed valence oxide thermocouples and thermionic vacuum-tube schemes.

The thermionic converters may reject heat at high enough temperature levels to make cascading of several conversion schemes appear attractive. For example, as shown in Fig. 4, a thermionic diode could receive heat at 2400F and reject it

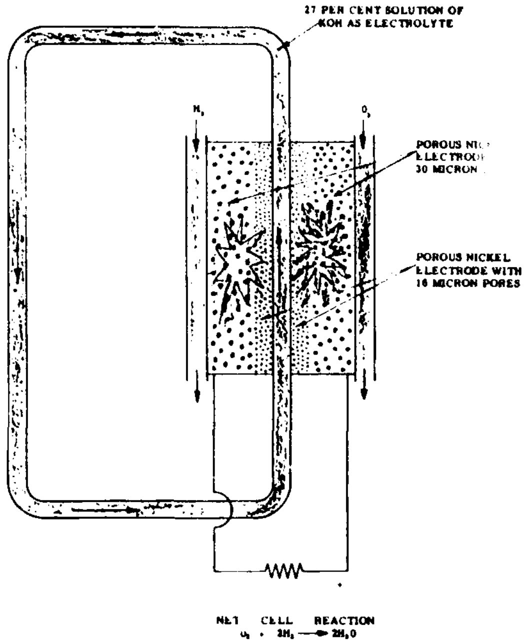


Fig.5 Hydrox cell.

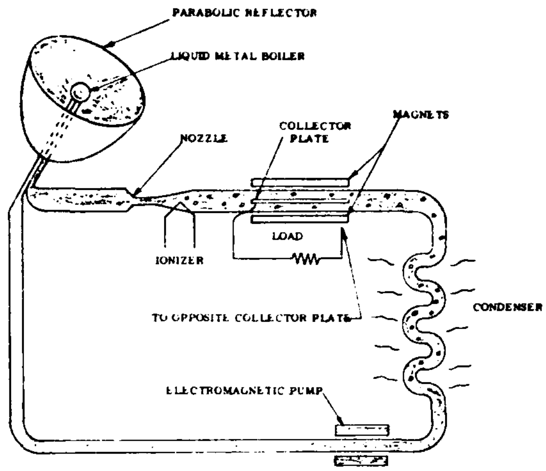


Fig.6 Magnetohydrodynamic method of direct conversion of solar heat into electrical energy.

at 1200F to a mercury Rankine cycle, which in turn could reject its heat to a mixed valence oxide thermopile cooled by the radiator.

If each of these schemes had an efficiency of 5 per cent, the over-all efficiency would exceed 14 per cent. Unfortunately, while such cascading of conversion schemes would be beneficial from the standpoint of efficiency, reliability would be adversely affected, since the over-all system reliability would be the product of the reliability fraction of each element of the cascade.

Chemical Conversion

Fig. 5 shows a very efficient chemical-conversion scheme for short-duration power requirements, where it is possible to store the hydrogen and oxygen necessary for the reaction. The product of the Hydrox Cell reaction is water. To use this idea for a long-duration power supply would require a means for disassociation of the water back into hydrogen and oxygen.

Indirect Conversion

If solar or nuclear heat are converted to fluid kinetic energy, for example, by boiling a liquid metal such as mercury, several indirect conversion schemes are possible.

Fig. 6 shows a method of converting the kinetic energy of an ionized gas directly into electrical energy. Fig. 7 is a photograph of an experimental converter tube designed for mercury vapor.

Mechanical Heat Engine

The least direct of all the conversion schemes, and yet the most advanced in technology, is the mechanical heat engine driving a generator or alternator.

While reciprocating heat engines are possible from a thermodynamic standpoint, the turbine has fewer mechanical development problems and offers lower weight-power ratios, particularly in the power range above a few kilowatts.

Heat-Source Selection

The power-conversion cycle using turbomachinery is not grossly affected by the choice of nuclear or solar-heat input to the cycle. At the present state of power-reactor technology, the nuclear cycle is inherently more temperature-limited than the solar cycle, because of metallurgical limitations in the reactor core which are more severe than those in a solar collector and boiler. For the purpose of this discussion, either solar or nuclear heat sources may be assumed.

Cycle Selection

The Brayton, Rankine, or modifications of these closed cycles, are potential choices. Detailed cycle studies confirm the advantages of the Rankine cycle, or modifications of the Rankine cycle, for temperature extremes compatible with present metallurgical limitations and the heat-transfer limitations in space. The superior heat transfer of boiling and condensing liquids further reduces the size of Rankine cycle heat exchangers over that of the Brayton cycle. Fig. 8 shows the schematic similarity of the nuclear and solar Rankine cycles.

Fig.7 Magnetohydrodynamic conversion.

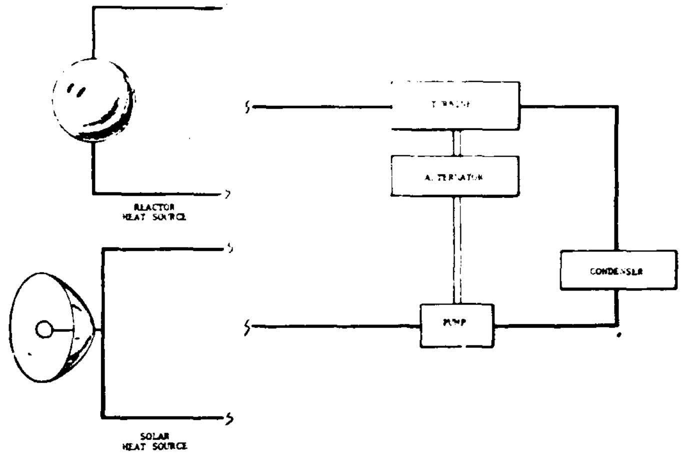


Fig.8 Closed Rankine-cycle system using either nuclear heat or solar heat.

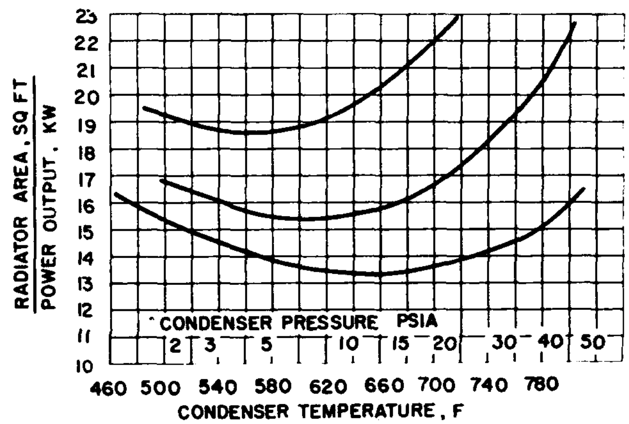


Fig.9 Condenser temperature versus radiator area.

TABLE 2 RANKINE CYCLE WORKING FLUIDS

FLUID	MELTING POINT (F)	NORMAL BOILING POINT (F)	HEAT OF VAPORIZATION Btu/lb
WATER	32	212	970
MERCURY	-38	674	127
SULFUR	238	832	124
RUBIDIUM	102	1254	381
SODIUM	207	1620	1808
POTASSIUM	143	1400	874
CESIUM	83	1274	221
SELENIUM	122	1270	122
ALUMINUM BROMIDE	208	484	41
BISMUTH TRICHLORIDE	435	826	99
ZINC CHLORIDE	541	1349	378

Working-Fluid Selection

Table 2 shows a wide choice of potential working substances for Rankine cycles, based upon physical properties alone. This list narrows down very rapidly when factors such as corrosion, radiation damage, and desirable cycle temperatures are taken into consideration.

Water and mercury are the only fluids which have been used extensively in the past for vapor turbines in the temperature range of interest to space applications. Mercury fits the temperature spectrum for space applications better than water.

The vacuum surrounding the space vehicle behaves like the liner in a thermos bottle, permitting heat removal from the power cycle only in the form of radiation. Radiant-heat energy is emitted in proportion to the difference between the fourth power of the absolute temperature of the radiator and the equivalent absolute temperature of the areas "seen" by the radiator. In the case of a space power system, this receiving temperature will be a mean value, depending upon how much of the earth, sun, and free space are seen by the radiator. For a satellite with a day-night orbit several hundred miles above the earth, the receiving temperature will vary from about -100 to +50 F, depending upon the orbit and the orientation of the radiator. If the bottom cycle temperature were as low as 80 F, as it is in large, efficient, steam power plants, the cycle could be efficient but the radiator would be enormous because of the small temperature difference available for heat transfer by radiation.

As we increase the radiator temperature, then, the radiator will get smaller, in accordance with the fourth-power law, but the cycle will get less efficient, hence there will be more heat to dump. There is an optimum bottom temperature for each cycle selected, which will result in a minimum radiator size for a given useful power output. This relationship is shown in Fig. 9.

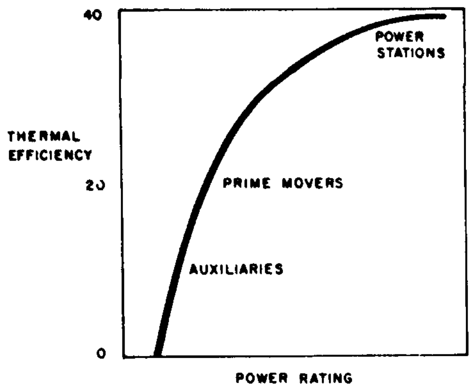


Fig.10 Power rating versus thermal efficiency.

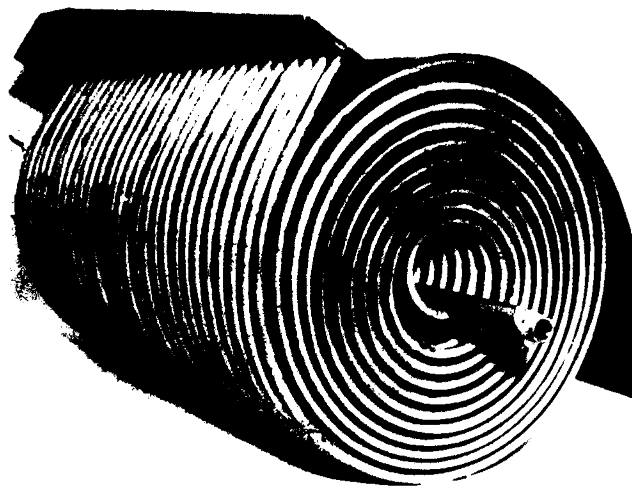


Fig.11 Zero g condenser.

Over-all cycle conversion efficiency is important to the space-power-plant designer, not from the usual standpoint of fuel economy, but from the standpoint of size and weight of equipment. The solar collector, heat exchanger, and radiator of a 5 per cent efficient power cycle are, roughly, twice as large as those on a 10 per cent efficient cycle.

Since cycle efficiency so critically affects component size, a discussion of the factors affecting efficiency is appropriate.

As shown in Fig. 10, large, modern, high-temperature steam power plants for public utilities have over-all efficiencies measured from fuel heat value to useful electrical power output of the order of 35 to 40 per cent. These values are achieved only because size and complexity of power plants are secondary factors. The most efficient of the modern marine steam propulsion plants run 30-35 per cent in efficiency. Central station and marine nuclear power plants currently in operation have efficiencies of the order of 20 per cent, or less. Modern open-cycle, gas-turbine-generator plants for aircraft use have over-all efficiencies of the order of 10 to 15 per cent. Small chemical-fueled APU's for missiles with outputs of 5 kw, or less, have efficiencies less than 10 per cent. Presently conceived long-duration power-conversion schemes appear to have conversion efficiencies in the range of a fraction of 1 to 7 per cent. In some cases the quoted efficiency figures reflect the development status in a paradoxical manner -- the more the experimenter has worked with his scheme, the lower his figures of promised efficiencies.

There are concrete reasons why small size has an adverse effect on cycle efficiency. In very large turbines, for example, the flow passages are large compared to the parasitic boundary-layer flow. In very small reciprocating engines and turbines, the frictional boundary layers may be comparable in thickness to the working-fluid stream. In large machinery, bearing frictional losses are a negligible fraction of power output. In a 10-hp turbine operating at 36,000 rpm, bearing friction for conventional oil-lubricated bearings may run several horsepower, or a substantial fraction of the useful power output. Other parasitic losses of power plants, such as auxiliary pumps and controls, cannot be scaled down in size. Pumping power, for example, may run only 1 per cent of the useful power output of a large steam plant, but 20 per cent, or more, of the useful output of a very small vapor cycle.

DEVELOPMENTAL PROBLEMS

While turbomachinery technology is well advanced, compared to the direct-conversion schemes, the application to long duration, unattended, space power plants poses some severe developmental problems.

Space Problems

The absence of gravity requires special design provisions for the separation of vapor and liquid phases in the boiler and the condenser. Without this separation in the condenser, for example, it would not be possible to provide a net positive suction head of liquid for the boiler feed pump. Fig. 11 is a photograph of a condenser which works successfully in spite of gravity, hence should perform even better in the absence of gravity.

In general, if a component is designed to function under 1 g acceleration in any direction,

it should function in the absence of gravity. As a word of warning, it is possible to design components which defy this rule of thumb.

<u>Temperature</u> The problem of rejecting heat in space has already been mentioned. The space-vehicle designer will probably find that the surface area needed for heat dissipation by radiation is large, and may require extended surfaces. A corollary to this is that low-temperature heat sinks for

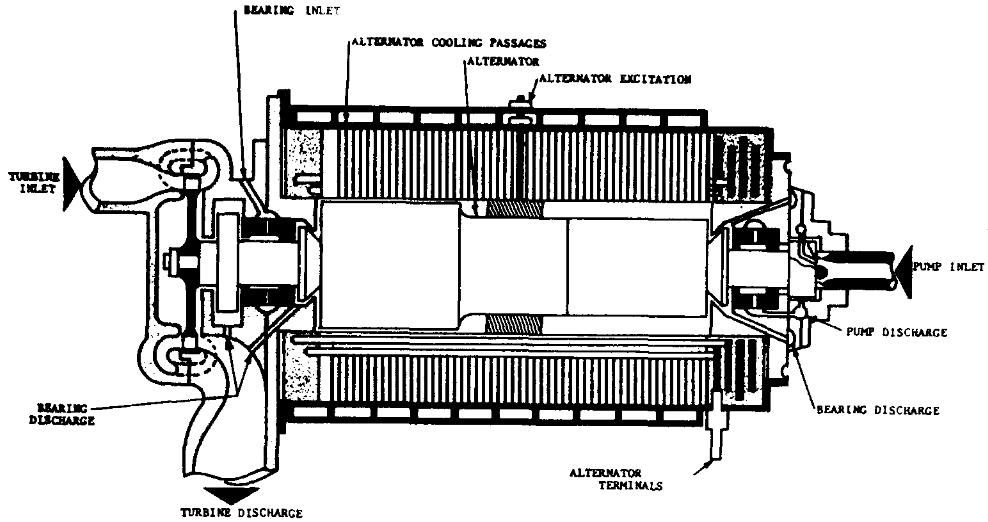


Fig.12 Combined shaft unit.

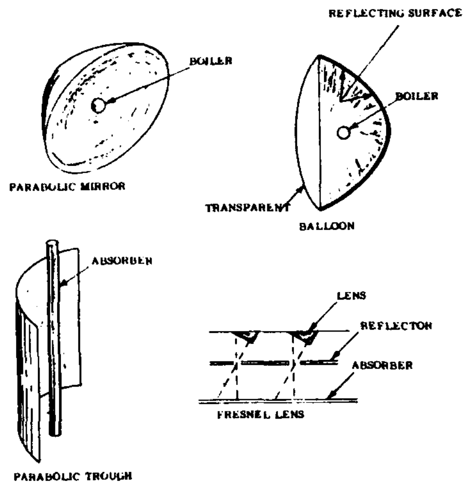


Fig.13 Solar-concentrator concepts.

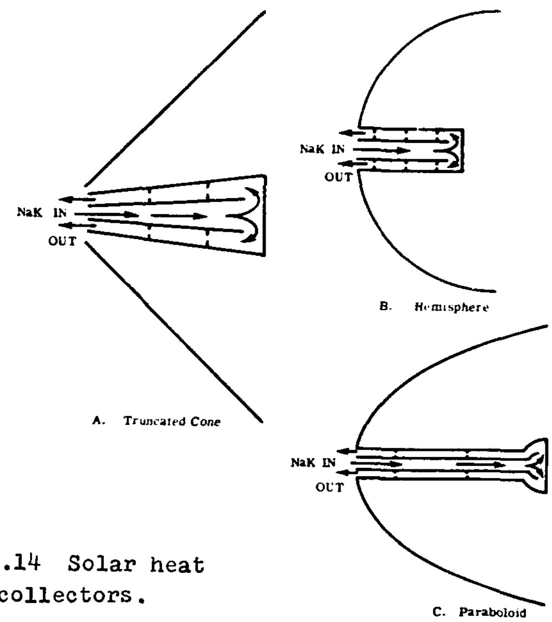


Fig.14 Solar heat collectors.

comfort cooling or for electronic cooling will be expensive energy-wise, since they will require refrigeration to obtain temperature below that of the radiator.

<u>Cycle Fluid Selection</u>

While water and, to a lesser extent, mercury, are the only Rankine cycle working substances with an appreciable technology built around them, and hence must not be discounted for space applications of the near future, other fluids such as sulfur and rubidium, have inherent properties which make them worthy of study as future working substances, provided the problems of materials with these fluids can be solved.

<u>Engineering Problems</u>

Engineering problems common to closed turbomachinery cycles, regardless of the cycle fluid selection, are:

<u>Leakage.</u> The 100 per cent reliable, leakless, rotating shaft seal has yet to be developed, as demonstrated by the spots on your garage floor. Since the satellite power supply will be called upon to perform reliably without maintenance or adjustment for long periods of time (say, several weeks to three years), leakage of the working fluid, or interleakage of working fluids, lubricants, and cooling fluids cannot be tolerated. One approach to the leakage problem is to use the working substance as a bearing lubricant and eliminate the usual shaft seal between the turbine and the alternator. This leaves the alternator designer with two choices, either of them highly developmental: (1) Allow the rotor cavity to fill with the working substance, sealing

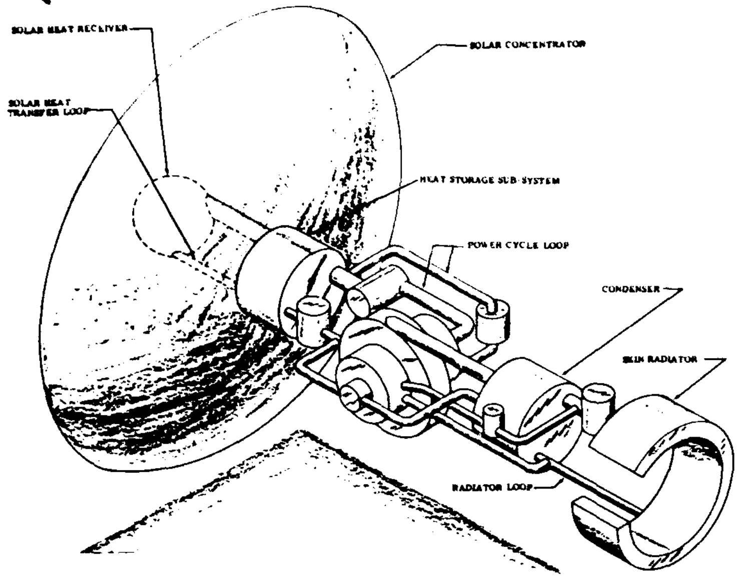


Fig.15 Three loop - solar APU.

it from the stator windings and laminations by a hermetically sealed can; or (2) use a potting compound to protect the stator windings and laminations against the working substance. Fig. 12 is a schematic cross-section view of a hermetically sealed turbine alternator and pump on a common shaft.

Bearings. While sleeve bearings can be designed to work with nearly any fluid, finding compatible bearing materials which are also resistant to corrosion in the chosen cycle fluid poses quite a problem. As mentioned previously, bearing-friction losses in a small, high-speed turbine can represent a large fraction of useful shaft output power. Recent work with vapor-lubricated bearings offers some promise of lowering friction losses; however, the load-carrying capacity of this type of bearing is inherently low. To further aggravate the bearing problem, the space power plant, if started on the ground, may be subjected to relatively high acceleration loads during launch. Thus the bearings need to be oversized to handle this brief load.

Pump Design

In order to eliminate reduction gearing, with attendant lubrication problems, it is desirable to drive the boiler feed pump from the common turbine-alternator shaft. This requirement leads to the development of extremely high, specific speed fluid pumps.

Solar Collector Design

For a 5-kw power supply, the solar collector must have an area the equivalent of a 40 to 60-ft-diam parabolic reflector. Erecting and orienting a close-tolerance surface of this size in space is admittedly quite a mechanical engineering problem. Fig. 13 shows several possible solar concentrator concepts. Fig. 14 shows several schemes for transferring heat between solar collectors and fluid boilers.

System Design

The weight optimization of a solar or nuclear heated turbomachinery power plant for space application requires a detailed design study of the interaction of design parameters for each component in the system. It should be remembered that there is nothing about small size which permits the simplification or reduction of any of the components normally required in a large closed-cycle power plant. Fig. 15 shows schematically the basic components in a three-loop solar-heated space power supply.

CONCLUSION

The storage-battery power supply in the first ATLAS missile to be placed into orbit around the earth had an endurance of about one half the lifetime of the vehicle in orbit. The power supply in the sun-orbiting Soviet satellite "Lunik" failed 65 hr after launch. It is painfully apparent that space-vehicle launch capability far exceeds the development status of any of the many schemes for long-duration power supplies.

Of these schemes, the use of turbomachinery in a closed-heat-engine cycle, such as the Rankine cycle, appears to be the most readily available for power supplies above a few kilowatts.

Even this approach, however, will require substantial additional developments before reliable long-duration power supplies are available "off the shelf."